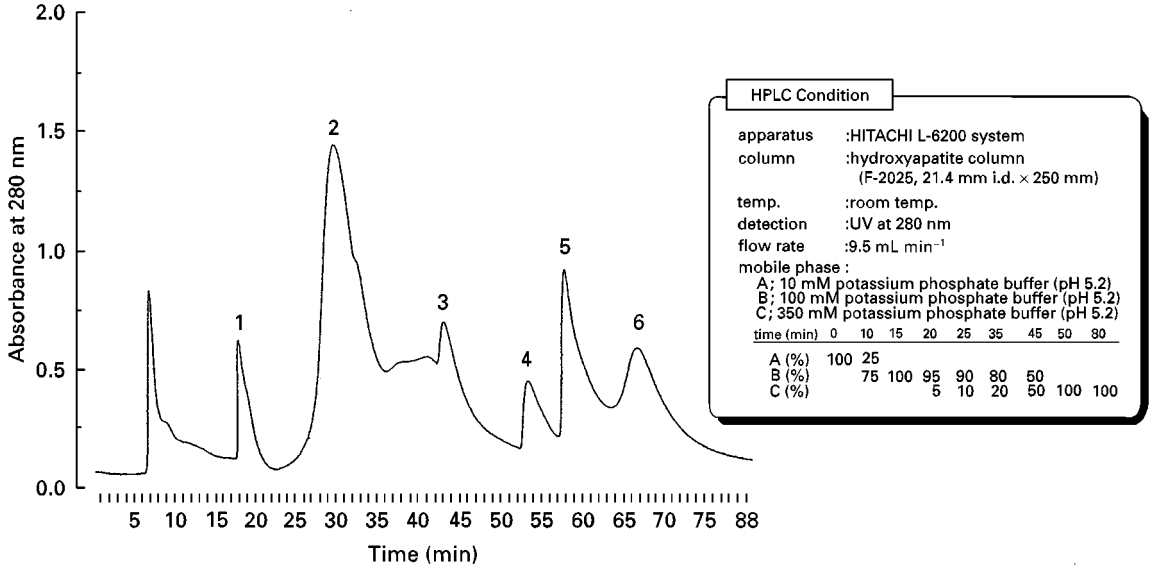
2.0
1.5
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Absorbance at 280 nm
1
2
3
4
5
6
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 88
Time (min)
HPLC Condition
apparatus :HITACHI L-6200 system
column :hydroxyapatite column
(F-2025, 21.4 mm i.d. × 250 mm)
temp. :room temp.
detection :UV at 280 nm
flow rate :9.5 mL min⁻¹
mobile phase :
A; 10 mM potassium phosphate buffer (pH 5.2)
B; 100 mM potassium phosphate buffer (pH 5.2)
C; 350 mM potassium phosphate buffer (pH 5.2)
time (min) 0 10 15 20 25 35 45 50 80
A (%) 100 25
B (%) 75 100 95 90 80 50
C (%) 5 10 20 50 100 100

Figure 4 Typical chromatograms of the glycoforms of α_1-acid glycoprotein (AAG) from the serum of healthy subjects by HPLC. Inlet is the gradient programme for the fractionation of the glycoforms of AAG. (Sampling time of each fraction: fraction 1, 17–22 min; 2, 27–36 min; 3, 43–50 min; 4, 53–57 min; 5, 58–62 min and 6, 65–72 min.) (Reproduced with permission from Kishino *et al.*, 1997.)

See also: **III/Carbohydrates:** Liquid Chromatography. **Peptides and Proteins:** Liquid Chromatography. **Polysaccharides:** Liquid Chromatography.

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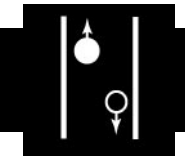
GOLD RECOVERY: FLOTATION



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Introduction

The recovery of gold from gold-bearing ores depends largely on the nature of the deposit, the mineralogy of the ore and the distribution of gold in the ore. The methods used for the recovery of gold consist of the following unit operations:

- The gravity preconcentration method, which is mainly used for recovery of gold from placer deposits that contain coarse native gold. Gravity is

often used in combination with flotation and/or cyanidation.

- Hydrometallurgical methods are normally employed for recovery of gold from oxidized deposits (heap leach), low grade sulfide ores (cyanidation, carbon-in-pulp (CIP), carbon-in-leach (CIL)) and refractory gold ores (autoclave, biological decomposition followed by cyanidation).
- A combination of pyrometallurgical (roasting) and hydrometallurgical route is used for highly refractory gold ores (carbonaceous sulfides, arsenical gold ores) and the ores that contain impurities that result in a high consumption of cyanide, which have to be removed before cyanidation.
- The flotation method is a widely used technique for the recovery of gold from gold-containing copper ores, base metal ores, copper–nickel ores, platinum group ores and many other ores where other processes are not applicable. Flotation is also used for the removal of interfering impurities before hydrometallurgical treatment (i.e. carbon prefloat), for upgrading of low sulfide and refractory ores for further treatment. Flotation is considered to be the most cost-effective method for concentrating gold.

Significant progress has been made over the past several decades in the recovery of gold using hydrometallurgical methods, including cyanidation (CIL, resin-in-pulp) and bio-oxidation. All of these processes are well documented in the literature and abundantly described. However, very little is known about the flotation properties of gold contained in various ores and the sulfides that carry gold. The sparse distribution of discrete gold minerals, as well as their exceedingly low concentrations in the ore, is one of the principal reasons for the lack of fundamental work on the flotation of gold-bearing ores.

In spite of the lack of basic research on flotation of gold-bearing ores, the flotation technique is used, not only for upgrading of low grade gold ore for further treatment, but also for beneficiation and separation of difficult-to-treat (refractory) gold ores. Flotation is also the best method for recovery of gold from base metal ores and gold-containing platinum group metals (PGM) ores. Excluding gravity preconcentration, flotation remains the most cost-effective beneficiation method.

Gold itself is a rare metal and the average grades for low grade deposits vary between 3 and 6 p.p.m. Gold occurs predominantly in its native form in silicate veins, alluvial and placer deposits or encapsulated in sulfides. Other common occurrences of gold are alloys with copper, tellurium, antimony, selenium, PGMs and silver. In massive sulfide ores, gold may occur in several of the above forms, which affects flotation recovery.

During flotation of gold-bearing massive sulfide ores, the emphasis is generally placed on the production of base metal concentrates and gold recovery becomes a secondary consideration. In some cases, where significant quantities of gold are contained in base metal ores, the gold is floated from the base metal tailings.

The flotation of gold-bearing ores is classified according to ore type (i.e. gold ore, gold–copper ore, gold–antimony ores), because the flotation methods used for the recovery of gold from different ores is vastly different.

Geology and General Mineralogy of Gold-bearing Ores

The geology of the deposit and the mineralogy of the ore play a decisive role in the selection of the best treatment method for a particular gold ore. Geology of the gold deposits varies considerably, not only from deposit to deposit, but also within the deposit. **Table 1** shows major genetic types of gold ores and their mineral composition. More than 50% of the total world gold production comes from clastic sedimentary deposits.

In many geological ore types, several subtypes can be found, including primary ores, secondary ores and

Table 1 Common genetic types of gold deposits

Ore type	*Description*
Magmatic	Gold occurs as an alloy with copper, nickel and platinum group metals Typically contains low amount of gold
Ores in clastic sedimentary rock	Placer deposits, in general conglomerates, which contain quartz, sericite, chlorite, tourmaline and sometimes rutile and graphite. Gold can be coarse. Some deposits contain up to 3% pyrite. Size of the gold contained in pyrite ranges from 0.01 to 0.07 μm
Hydrothermal	This type contains a variety of ores, including: Gold–pyrite ores Gold–copper ores Gold–polymetallic ores Gold–oxide ore, usually upper zone of sulfide zones The pyrite content of the ore varies from 3% to 90%. Other common waste minerals are quartz, aluminosilicates, dolomite
Metasomatic or scarn ores	Sometimes very complex and refractory gold ores. Normally the ores are composed of quartz, sericite, chlorites, calcite, magnetite. Sometimes the ore contains wolframite and sheelite

Table 2 Major gold minerals

Group	*Mineral*	*Chemical formula*	*Impurity content*
Native gold and its alloys	Native gold	Au	0–15% Ag
	Electrum	Au/Ag	15–50% Ag
	Cuproauride	Au/Cu	5–10% Cu
	Amalgam	Hg/Au	10–34% Au
	Bismuthauride	Au/Bi	2–4% Bi
Tellurides	Calaverite	$AuTe_2$	
	Sylvanite	$(Au, Ag)Te_2$	
	Petzite	(Au, Ag)Te	
	Magyazite	$Au(Pb, Sb, Fe)(S, Te_{II})$	Unstable
Gold associated with platinum group metals	Krennerite	$AuTe_2(Pt, Pl)$	
	Platinum gold	AuPt	Up to 10% Pt
	Rhodite	AuRh	30–40% Rh
	Rhodian gold	AuRh	5–11% Rh
	Aurosmiride	Au, Ir, Os	5% Os + 5–7% Ir

oxide ores. Some of the secondary ores belong to a group of highly refractory ores, such as those from Nevada (USA), and El Indio (Chile). The number of gold minerals and their associations are relatively small and can be divided into the following three groups: native gold and its alloys, tellurides and gold associated with PGMs.

Table 2 lists major gold minerals and their associations.

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Flotation Properties of Gold Minerals and Factors Affecting Floatability

Native gold and its alloys, which are free from surface contaminants, are readily floatable with xanthate collectors. Very often, however, gold surfaces are contaminated or covered with varieties of impurities. The impurities present on gold surfaces may be argentite, iron oxides, galena, arsenopyrite or copper oxides. The thickness of the layer may be in the order of 1–5 μm. Because of this, the flotation properties of native gold and its alloys vary widely. Gold covered with iron oxides or oxide copper is very difficult to float and requires special treatment to remove the contaminants.

Tellurides on the other hand are readily floatable in the presence of small quantities of collector, and it is believed that tellurides are naturally hydrophobic. Tellurides from Minnesota (USA) were floated using dithiophosphate collectors, with over 95% gold recovery.

Flotation behaviour of gold associated in the platinum group metals is apparently the same as that for the PGMs or other minerals associated with the PGMs (i.e. nickel, pyrrhotite, copper and pyrite). Therefore, the reagent scheme developed for PGMs also recovers gold. Normally, for the flotation of PGMs and associated gold, a combination of xanthate and dithiophosphate is used, along with gangue depressants guar gum, dextrin or modified cellulose. In the South African PGM operations, gold recovery into the PGM concentrate ranges from 75% to 80%.

Perhaps the most difficult problem in flotation of native gold and its alloys is the tendency of gold to plate, vein, flake and assume many shapes during grinding. Particles with sharp edges tend to detach from the air bubbles, resulting in gold losses. This shape factor also affects gold recovery using a gravity method.

In flotation of gold-containing base metal ores, a number of modifiers normally used for selective flotation of copper–lead, lead–zinc and copper–lead–zinc have a negative effect on the floatability of gold. Such modifiers include $ZnSO_4 \times 7H_2O$, SO_2, $Na_2S_2O_5$, and cyanide when added in excessive amounts.

The adsorption of collector on gold and its floatability are considerably improved by the presence of oxygen. **Figure 1** shows the relationship between collector adsorption, oxygen concentration in the pulp and conditioning time. The type of modifier and the pH are also important parameters in flotation of gold.

Flotation of Low Sulfide-containing Gold Ores

The beneficiation of this ore type usually involves a combination of gravity concentration, cyanidation and flotation. For an ore with coarse gold, gold is often recovered by gravity and flotation, followed by cyanidation of the reground flotation concentrate. In some cases, flotation is also conducted on the cyanidation tailing. The reagent combination used in flotation depends on the nature of gangue present in the ore. The usual collectors are xanthates,

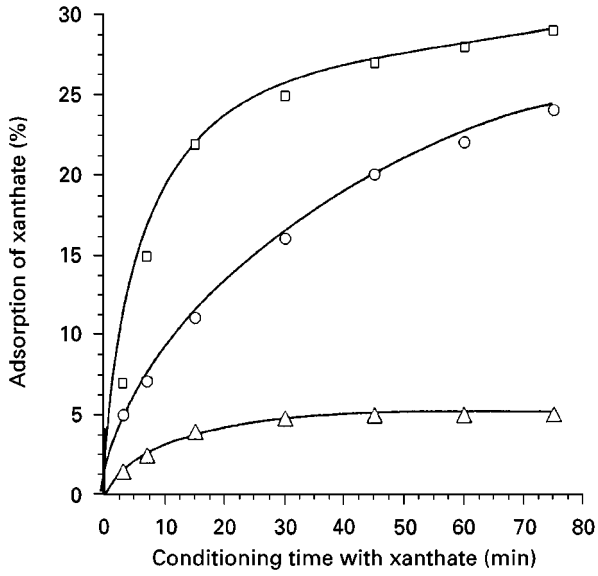

Figure 1 Relationship between adsorption of xanthate on gold and conditioning time in the presence of various concentrations of xanthate. Triangles, O_2 2 mg L^{-1}, circles; O_2 9 mg L^{-1}; squares, O_2 45 mg L^{-1}.

dithiophosphates and mercaptans. In the scavenging section of the flotation circuit, two types of collector are used as secondary collectors. In the case of a partially oxidized ore, auxiliary collectors, such as hydrocarbon oils with sulfidizer, often yield improved results. The preferred pH regulator is soda ash, which acts as a dispersant and also as a complexing reagent for some heavy metal cations that have a negative effect on gold flotation. Use of lime often results in the depression of native gold and gold-bearing sulfides. The optimum flotation pH ranges between 8.5 and 10.0. The type of frother also plays an important role in the flotation of native gold and gold-bearing sulfides. Glycol esters and cyclic alcohols (pine oil) can improve gold recovery significantly.

Amongst the modifying reagents (depressant), sodium silicate starch dextrins and low molecular weight polyacrylamides are often selected as gangue depressants. Fluorosilicic acid and its salts can also have a positive effect on the floatability of gold. The presence of soluble iron in a pulp is highly detrimental to gold flotation. The use of small quantities of iron-complexing agents, such as polyphosphates and organic acids, can eliminate the harmful effect of iron.

Flotation of Gold-containing Mercury/Antimony Ores

In general, these ores belong to a group of difficult-to-treat ores, where cyanidation usually produces poor extraction. Mercury is partially soluble in cyanide, which increases cyanide consumption and reduces extraction. A successful flotation method has been developed using the flow sheet shown in **Figure 2**, where the best metallurgical results were obtained using a three-stage grinding and flotation approach. The metallurgical results obtained with different grinding configurations are shown in **Table 3**.

Flotation was carried out at an alkaline pH, controlled by lime. A xanthate collector with cyclic alcohol frother (pine oil, cresylic acid) was shown to be the most effective. The use of small quantities of a dithiophosphate-type collector, together with xanthate, was beneficial.

Flotation of Carbonaceous Clay-containing Gold Ores

These ores belong to a group of refractory gold ores, where flotation techniques can be used to remove interfering impurities before the hydrometallurgical treatment process of the ore for gold recovery and to preconcentrate the ore for further pyrometallurgical or hydrometallurgical treatment. There are several flotation methods used for beneficiation of this ore type. Some of the most important methods are described as follows:

- Preflotation of carbonaceous gangue and carbon. In this case, only carbonaceous gangue and carbon are recovered by flotation, in preparation for further hydrometallurgical treatment of the float tails for gold recovery. Carbonaceous gangue and carbon are naturally floatable using only a frother, or a combination of a frother and a light hydrocarbon oil (fuel oil, kerosene). When the ore contains clay, regulators for clay dispersion are used. Some of the more effective regulating reagents include sodium silicates and oxidized starch.
- Two-stage flotation method. In this case, carbonaceous gangue is prefloated using the method described above, followed by flotation of gold-containing sulfides using activator–collector combinations. In extensive studies conducted on carbonaceous gold-containing ores, it was established that primary amine-treated copper sulfate improved gold recovery considerably. Ammonium salts and sodium sulfide ($Na_2S \times 9H_2O$) also have a positive effect on gold-bearing sulfide flotation, at a pH between 7.5 and 9.0. The metallurgical results obtained with and without modified copper sulfate are shown in **Table 4**.
- Nitrogen atmosphere flotation method. This technique uses a nitrogen atmosphere in grinding and flotation to retard oxidation of reactive sulfides, and has been successfully applied on carbonaceous ores from Nevada (USA). The effectiveness of the method depends on the amount of carbonaceous gangue present in the ore, and the amount and type

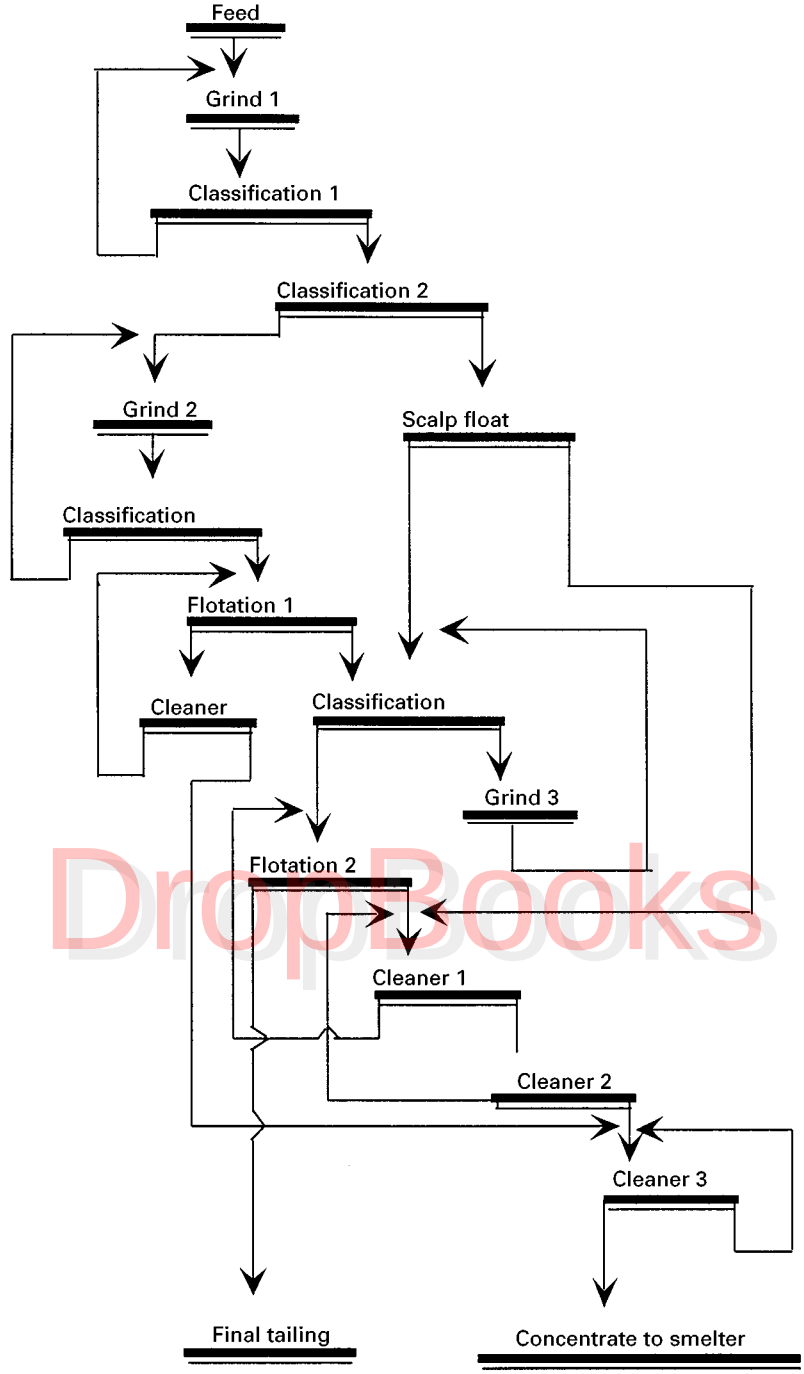

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Figure 2 Flotation flow sheet developed for the treatment of gold-containing mercury–antimony ore.

of clay. Ores that are high in carbon or contain high clay content (or both) are not amenable for nitrogen atmosphere flotation.

Flotation of Gold-containing Copper Ores

The floatability of gold from gold-containing copper–gold ores depends on the nature and occurrence of gold in these ores, and its association with iron sulfides.

Gold in the porphyry copper ore may appear as native gold, electrum, cuproaurid and sulfosalts associated with silver. During the flotation of porphyry copper–gold ores, emphasis is usually placed on the production of a marketable copper–gold concentrate and optimization of gold recovery is usually constrained by the marketability of its concentrate.

Table 3 Gold recovery obtained using different flow sheets

Flow sheet	*Recovery in concentrate (%)*					*Tailing Assays (%, g t^{-1})*				
	Au	*Ag*	*Sb*	*As*	*S*	*Au*	*Ag*	*Sb*	*As*	*S*
Single-stage grind flotation	88.1	89.2	72.9	68.4	70.1	1.7	5.0	0.04	0.035	0.38
Two-stage grind flotation	92.2	91.8	93.4	78.7	81.2	1.0	4.1	0.015	0.022	0.27
Three-stage grind flotation	95.3	95.2	95.7	81.2	85.7	0.7	2.2	0.005	0.015	0.19

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The minerals that influence gold recovery in these ores are iron sulfides (i.e. pyrite, marcasite), in which gold is usually associated as minute inclusions. Thus, the iron sulfide content of the ore determines gold recovery in the final concentrate. **Figure 3** shows the relationship between pyrite content of the ore and gold recovery in the copper concentrate for two different ore types. Most of the gold losses occur in the pyrite.

The reagent schemes used in commercial operations treating porphyry copper–gold ores vary considerably. Some operations, where pyrite rejection is a problem, use a dithiophosphate collector at an alkaline pH between 9.0 and 11.8 (e.g. OK Tedi, PNG Grasberg, Indonesia). When the pyrite content in the ore is low, xanthate and dithiophosphates are used in a lime or soda ash environment.

In more recent years, in the development of commercial processes for the recovery of gold from porphyry copper–gold ores, bulk flotation of all the sulfides has been emphasized, followed by regrinding of the bulk concentrate and sequential flotation of copper–gold from pyrite. Such a flow sheet (**Figure 4**) can also incorporate high intensity conditioning in the cleaner–scavenger stage. Comparison of metallurgical results using the standard sequential flotation flow sheet and the bulk flotation flow sheet is shown in **Table 5**. A considerable improvement in gold recovery was achieved using the bulk flotation flow sheet.

During beneficiation of clay-containing copper–gold ores, the use of small quantities of Na_2S (at natural pH) improves both copper and gold metallurgy considerably.

In the presence of soluble cations (e.g. Fe, Cu), additions of small quantities of organic acid (e.g. oxalic, tartaric) improve gold recovery in the copper concentrate.

Some porphyry copper ores contain naturally floatable gangue minerals, such as chlorites and aluminosilicates, as well as preactivated quartz. Sodium silicate, carboxymethylcellulose and dextrins are common depressants used to control gangue flotation.

Gold recovery from massive sulfide copper–gold ores is usually much lower than that of porphyry copper–gold ores, because very often a large portion of the gold is associated with pyrite. Normally, gold recovery from these ores does not exceed 60%. During the treatment of copper–gold ores containing pyrrhotite and marcasite, the use of $Na_2H_2PO_4$ at alkaline pHs depresses pyrrhotite and marcasite, and also improves copper and gold metallurgy.

Flotation of Oxide Copper–Gold Ores

Oxide copper–gold ores are usually accompanied by iron hydroxide slimes and various clay minerals. There are several deposits of this ore type around the world, some of which are located in Australia (Red Dome), Brazil (Igarape Bahia) and the Soviet Union (Kalima). Treatment of these ores is difficult, and even more complicated in the presence of clay minerals.

Recently, a new class of collectors, based on ester-modified xanthates, has been successfully used to treat gold-containing oxide copper ores, using a sulfidization method. **Table 6** compares the metallurgical results obtained on the Igarape Bahia ore using

Table 4 Effect of amine-modified $CuSO_4$ on gold-bearing sulfide flotation from carbonaceous refractory ore

Reagent used	*Product*	*Weight (%)*	*Assays (%, g t^{-1})*		*Distribution (%)*	
			Au	*S*	*Au*	*S*
$CuSO_4$ + xanthate	Gold sulfide conc.	30.11	9.63	4.50	69.1	79.7
	Gold sulfide tail	69.89	1.86	0.49	30.9	20.3
	Head	100.00	4.20	1.70	100.0	100.0
Amine modified	Gold sulfide conc.	26.30	13.2	5.80	84.7	90.8
$CuSO_4$ + xanthate	Gold sulfide tail	73.70	0.85	0.21	15.3	9.2
	Head	100.00	4.10	1.68	100.0	100.0

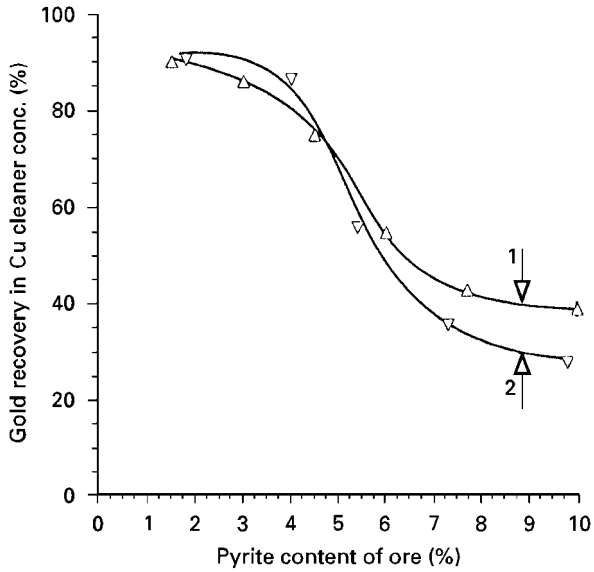

Figure 3 Effect of pyrite content of the ore on gold recovery in the copper–gold concentrate at 30% Cu concentrate grade. 1, Ore from Peru; 2, ore from Indonesia.

xanthate and a new collector (PM230, supplied by Senmin in South Africa).

The modifier used in the flotation of these ores included a mixture of sodium silicate and Calgon. Good selectivity was also achieved using boiled starch.

Flotation of Gold–Antimony Ores

Gold–antimony ores usually contain stibnite (1.5–4.0% Sb), pyrite, arsenopyrite gold (1.5–3.0 g t^{-1}) and silver (40–150 g t^{-1}). Several plants in the USA (Stibnite, Minnesota and Bradly) and Russia have been in operation for some time. There are two commercial processes available for treatment of these ores.

- Selective flotation of gold-containing sulfides followed by flotation of stibnite with pH change. Stibnite floats well in neutral and weak acid pH, while in an alkaline pH (i.e. > 8), it is reduced. Utilizing this phenomenon, gold-bearing sulfides are floated with xanthate and alcohol frother in alkaline medium (pH > 9.3) followed by stibnite flotation at about pH 6.0, after activation with lead nitrate. Typical metallurgical results using this method are shown in **Table 7**.
- Bulk flotation followed by sequential flotation of gold-bearing sulfides, and depression of stibnite. This method was practised at the Bradly concentrator (USA) and consisted of the following steps: first, bulk flotation of stibnite and gold bearing sulfides at pH 6.5 using lead nitrate (Sb activator) and xanthate; second, the bulk concentrate is reground in the presence of NaOH (pH 10.5) and $CuSO_4$, and the gold-bearing sulfides are refloated with additions of small quantities of xanthate; third, cleaning of the gold concentrate in the presence of NaOH and NaHS. The plant metallurgical results employing this method are shown in **Table 8**.

Recent studies conducted on ore from Kazakhstan have shown that sequential flotation using thionocarbamate collector gave better metallurgical results than those obtained with xanthate.

Flotation of Arsenical Gold Ores

There are two major groups of arsenical gold ores of economic value. These are the massive base metal sulfides with arsenical gold (e.g. the lead–zinc Olympias deposit, Greece) and arsenical gold ores without the presence of base metals. Massive, base metal arsenical gold ores are rare, and there are only a few deposits in the world. A typical arsenical gold ore contains arsenopyrite as the major arsenic mineral. However, some arsenical gold ores, such as those from Nevada in the USA (Getchel deposit), contain realgar and orpiment as the major arsenic-bearing

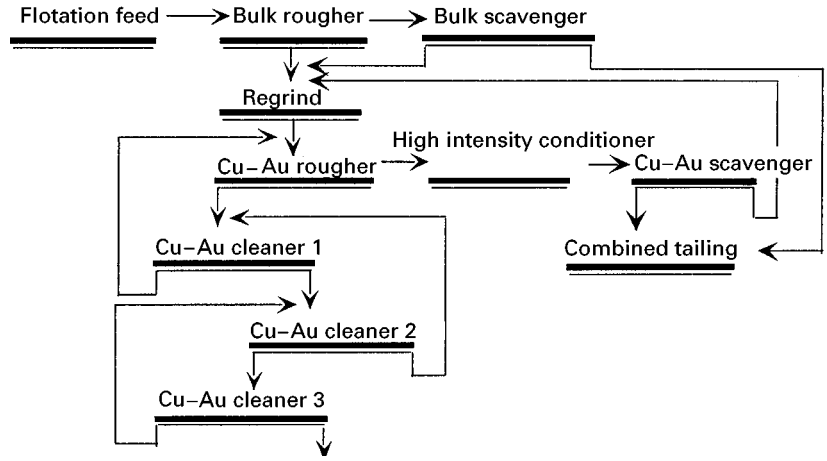

Figure 4 Bulk flow sheet used in the treatment of pyritic copper–gold ores. Reproduced with permission from Bulatovic (1997).

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Table 5 Comparison of metallurgical results using conventional and bulk flotation flow sheets on ore from Peru

Flow sheet used	*Product*	*Weight (%)*	*Assays (%, g t^{-1})*		*Distribution (%)*	
			Cu	*Au*	*Cu*	*Au*
Conventional (sequential Cu/Au)	Cu/Au conc.	2.28	27.6	32.97	95.4	76.7
	Cu/Au tail	97.72	0.031	0.23	4.6	23.3
	Head	100.00	0.66	0.98	100.0	100.0
Bulk (Figure 4)	Cu/Au conc.	2.32	27.1	36.94	95.2	85.8
	Cu/Au tail	97.68	0.032	0.14	4.8	14.2
	Head	100.00	0.66	0.96	100.0	100.0

minerals. Pyrite, if present in an arsenical gold ore, may contain some gold as minute inclusions.

Flotation of arsenical gold ores associated with base metals is accomplished using a sequential flotation technique, with flotation of base metals followed by flotation of gold-containing pyrite–arsenopyrite. The pyrite–arsenopyrite is floated at a weakly acid pH with a xanthate collector.

Arsenical gold ores that do not contain significant base metals are treated using a bulk flotation method, where all the sulfides are first recovered into a bulk concentrate. In case the gold is contained either in pyrite or arsenopyrite, separation of pyrite and arsenopyrite is practised. There are two commercial methods available. The first method utilizes arsenopyrite depression and pyrite flotation, and consists of the following steps:

- Heat the bulk concentrate to 75°C at a pH of 4.5 (controlled by H_2SO_4) in the presence of small quantities of potassium permanganate or disodium phosphate. The temperature is maintained for about 10 min.
- Flotation of pyrite using either ethylxanthate or potassium butylxanthate as collector. Glycol frother is also usually employed in this separation.

This method is highly sensitive to temperature. **Figure 5** shows the effect of temperature on pyrite–arsenopyrite separation. In this particular case, most of the gold was associated with pyrite. Successful pyrite–arsenopyrite separation can also be achieved with the use of potassium peroxydisulfide as the arsenopyrite depressant.

The second method involves depression of pyrite and flotation of arsenopyrite. In this method, the bulk concentrate is treated with high dosages of lime (pH > 12), followed by a conditioning step with $CuSO_4$ to activate arsenopyrite. The arsenopyrite is then floated using a thionocarbamate collector.

Separation of arsenopyrite and pyrite is important from the point of view of reducing downstream processing costs. Normally, roasting or pressure oxidation followed by cyanidation is used to recover gold.

Flotation of Gold from Base Metal Sulfide Ores

Very often lead–zinc, copper–zinc, copper–lead–zinc and copper–nickel ores contain significant quantities of gold (i.e. between 1 and 9 g/t). The gold in these ore types is usually found as elemental gold. A large portion of the gold in these ores is finely disseminated in pyrite, which is considered nonrecoverable. Because of the importance of producing commercial-grade copper, lead and zinc concentrates, little or no consideration is given to improvement in gold recovery, although the possibility exists to optimize gold

Table 6 Effect of collector PM230 on copper–gold recovery from Igarape Bahia oxide copper–gold ore

Reagent used	*Product*	*Weight (%)*	*Assays (%, g t^{-1})*		*Distribution (%)*	
			Cu	*Au*	*Cu*	*Au*
$Na_2S = 2500$ g t^{-1}	Copper Cl conc.	9.36	33.3	14.15	67.0	50.0
PAX = 200 g t^{-1}	Copper tail	90.64	1.61	1.46	33.0	50.0
	Feed	100.00	4.65	2.65	100.0	100.0
$Na_2S = 2500$ g t^{-1}	Copper Cl conc.	10.20	39.5	21.79	88.0	85.5
PAX/PM230	Copper tail	89.80	0.61	0.42	12.0	14.5
(1 : 1) = 200 g t^{-1}	Feed	100.00	0.61	0.42	12.0	14.5

PAX, potassium amylxanthate.
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Table 7 Metallurgical results obtained using a sequential flotation method

Product	Weight (%)	Assays (%, g t^{-1})			Distribution (%)		
		Au	Ag	Sb	Au	Ag	Sb
Gold concentrate	2.34	42.3	269.3	20.0	53	13	15
Stibnite concentrate	4.04	6.2	559.8	51.0	13	51	64
Tailing	93.62	0.65	18.7	0.7	34	36	21
Feed	100.00	1.86	46.4	3.2	100	100	100

recovery in many cases. Normally, gold recovery from base metal ores ranges from 30 to 75%.

In the case of a copper–zinc and copper–lead–zinc ore, gold collects in the copper concentrate. During the treatment of lead–zinc ores, the gold tends to report to the lead concentrate. Information regarding gold recovery from base metal ores is sparse.

The most recent studies conducted on various base metal ores revealed some important features of flotation behaviour of gold from these ores. It has been demonstrated that gold recovery to the base metal concentrate can be substantially improved with the proper selection of reagent schemes. Some of these studies are discussed below.

Gold-containing lead–zinc ores Some of these ores contain significant quantities of gold, ranging from 0.9 to 6.0 g t^{-1} (e.g. Grum, Yukon, Canada; Greens Creek, Alaska and Milpo, Peru). The gold recovery from these ores ranges from 35 to 75%. Laboratory studies have shown that the use of high dosages of zinc sulfate, which is a common zinc depressant used in lead flotation, reduces gold floatability significantly. The effect of $ZnSO_4 \times 7H_2O$ addition on gold recovery in the lead concentrate is illustrated in **Figure 6**.

In order to improve gold recovery in the lead concentrate, an alternative depressant to $ZnSO_4 \times 7H_2O$ can be used. Depressant combinations such as $Na_2S + NaCN$, or $Na_2SO_3 + NaCN$, may be used. The type of collector also plays an important role in gold flotation of lead–zinc ores. A phosphine-based collector, in combination with xanthate, gave better gold recovery than dithiophosphates.

Copper–zinc gold-containing ores Gold recovery from copper–zinc ores is usually higher than that obtained from either a lead–zinc or copper–lead–zinc ore. This is attributed to two main factors. When selecting a reagent scheme for treatment of copper–zinc ores, there are more choices than for the other ore types, which can lead to the selection of a reagent scheme which is more favourable for gold flotation. In addition, a noncyanide depressant system can be used for the treatment of these ores, which in turn results in improved gold recovery. This option is not available during treatment of lead–zinc ores. **Table 9** shows the effect of different depressant combinations on gold recovery from a copper–zinc ore.

The use of a noncyanide depressant system resulted in a substantial improvement in gold recovery in the copper concentrate.

Gold-containing copper–lead–zinc ores Because of the complex nature of these ores, and the requirement for a relatively complex reagent scheme for treatment of this ore, the gold recovery is generally lower than that achieved from a lead–zinc or copper–zinc ore. One of the major problems associated with the flotation of gold from these ores is related to gold mineralogy. A large portion of the gold is usually contained in pyrite, at sub-micron size. If coarser elemental gold and electrum are present, the gold surfaces are often coated with iron or lead, which can result in a substantial reduction in floatability.

The type of collector and flow sheet configuration play an important role in gold recovery from these ores. With a flow sheet that uses bulk copper–lead flotation followed by copper–lead separation, the gold recovery is higher than that achieved with a

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Table 8 Plant metallurgical results obtained using a bulk flotation method

Product	Weight (%)	Assays (%, g t^{-1})			Distribution (%)		
		Au	Ag	Sb	Au	Ag	Sb
Gold concentrate	1.80	91.1	248.8	1.5	61.0	31.3	2.0
Antimony concentrate	1.80	13.0	684.2	51.3	9.0	58.6	75.0
Middlings	0.50	46.6	248.8	20.0	8.6	6.0	8.0
Bulk concentrate	4.10	51.7	440.0	29.0	78.6	85.9	85.0
Tailing	95.90	0.6	3.1	0.2	21.4	14.1	15.0
Feed	100.00	2.7	21.0	1.3	100.0	100.0	100.0

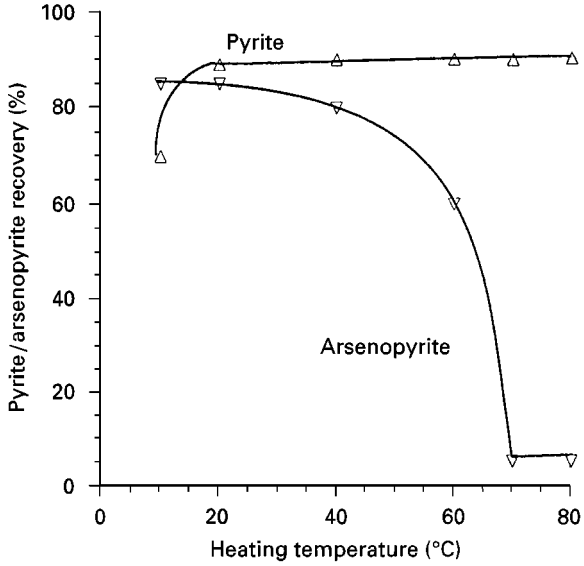

Figure 5 Effect of temperature on separation of pyrite and arsenopyrite from a bulk pyrite–arsenopyrite concentrate.

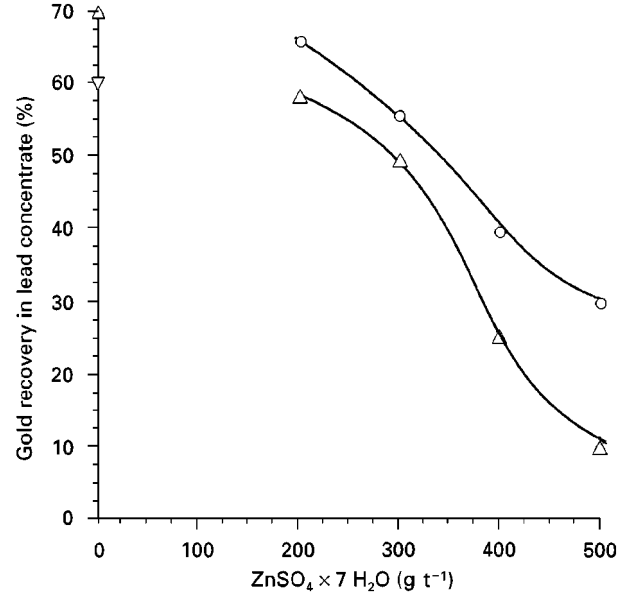

Figure 6 Effect of $ZnSO_4$ additions on gold recovery from lead–zinc ores. Circles, Greens Creek ore (Alaska); triangles, Grum ore Yukon (Canada).

sequential copper–lead flotation flow sheet. In laboratory tests, an aerophine collector type, in combination with xanthate, had a positive effect on gold recovery as compared to either dithiophosphate or thionocarbamate collectors. **Table 10** compares the metallurgical results obtained with an aerophine collector to those obtained with a dithiophosphate collector.

Because of the complex nature of gold-containing copper–lead–zinc ores, the reagent schemes used are also complex. Reagent modifiers such as $ZnSO_4$, NaCN and lime have to be used, all of which have a negative effect on gold flotation.

Conclusions

- The flotation of gold-bearing ores, whether for production of bulk concentrates for further gold recovery processes (i.e. pyrometallurgy, hydrometallurgy) or for recovery of gold to base metal concentrates, is a very important method for concentrating the gold and reducing downstream costs.
- The flotation of elemental gold, electrum and tellurides is usually very efficient, except when these minerals are floated from base metal massive sulfides.
- Flotation of gold-bearing sulfides from ores containing base metal sulfides presents many challenges and should be viewed as flotation of the particular mineral that contains gold (i.e. pyrite, arsenopyrite, copper), because gold is usually associated with these minerals at micron size.
- Selection of a flotation technique for gold preconcentration depends very much on the ore

Table 9 Effect of different depressant combinations on gold recovery to the copper concentrate from lower zone Kutcho Creek Ore

Depressant system	*Product*	*Weight (%)*	*Assays (%, g t^{-1})*			*Distribution (%)*		
			Au	*Cu*	*Zn*	*Au*	*Cu*	*Zn*
$ZnSO_4$, NaCN, CaO	Cu concentrate	3.10	20.4	26.2	3.30	45.1	85.6	2.8
pH 8.5 Cu, 10.5 Zn	Zn concentrate	5.34	1.20	0.61	55.4	4.6	3.4	82.2
	Tailings	91.56	0.77	0.11	0.58	50.3	11.0	15.0
	Feed	100.00	1.4	0.95	3.60	100.0	100.0	100.0
Na_2SO_3, NaHS, CaO	Cu concentrate	3.05	32.5	28.1	2.80	68.3	87.4	2.3
pH 8.5 Cu, 10.5 Zn	Zn concentrate	5.65	1.20	0.55	54.8	4.7	3.2	84.6
	Tailings	91.30	0.43	0.10	0.52	27.0	9.4	13.1
	Feed	100.00	1.45	0.98	3.66	100.0	100.0	100.0

Table 10 Effect of collector type on Cu-Pb-Zn-Au metallurgical results from a high lead ore

Collector used	*Product*	*Weight (%)*	*Assays (%, g t^{-1})*				*Distribution (%)*			
			Au	*Cu*	*Pb*	*Zn*	*Au*	*Cu*	*Pb*	*Zn*
Xanthate = 30 g/t	Cu concentrate	2.47	22.4	25.5	1.20	4.50	41.6	78.6	2.3	1.3
Dithiophosphate	Pb concentrate	1.80	2.50	0.80	51.5	8.30	3.4	1.8	71.3	1.7
3477 = 20 g/t	Zn concentrate	13.94	1.10	0.60	0.80	58.2	11.5	10.4	8.6	92.2
	Tailing	81.79	0.71	0.089	0.28	0.52	43.5	9.2	17.8	4.8
	Feed	100.00	1.33	0.80	1.30	8.80	100.0	100.0	100.0	100.0
Xanthate = 30 g/t	Cu concentrate	2.52	31.3	26.1	1.10	5.00	60.6	80.1	2.1	1.4
Aerophine 3418A = 20 g/t	Pb concentrate	1.92	2.80	0.90	51.1	9.20	4.1	2.1	72.5	2.0
	Zn concentrate	13.91	0.90	0.50	0.72	58.5	9.6	8.5	7.4	92.5
	Tailing	81.65	0.41	0.093	0.30	0.44	25.7	9.3	18.0	4.1
	Feed	100.00	1.30	0.82	1.35	8.80	100.0	100.0	100.0	100.0

mineralogy, gangue composition and gold particle size. There is no universal method for flotation of the gold-bearing minerals, and the process is tailored to the ore characteristics. A specific reagent scheme and flow sheet are required for each ore.

- There are opportunities on most operating plants for improving gold metallurgy. Most of these improvements come from selection of more effective reagent schemes, including collectors and modifiers.
- Perhaps the most difficult ores to treat are the clay-containing carbonaceous sulfides. Significant progress has been made in treatment options for these ores. New sulfide activators (e.g. amine-treated $CuSO_4$, ammonium salts) and nitrogen gas flotation are amongst the new methods available.

Further Reading

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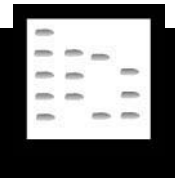

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Classical Precipitation Chromatography

Polymer Solubility and Precipitation

Solubility is governed by the general requirement that the change in Gibbs' free energy must be negative. With low molecular weight substances this condition is easily fulfilled, because the entropy contribution is large owing to the large number of particles involved. But with polymer compounds, the entropy of dissolution is comparatively small and the enthalpy contribution gains in importance. The precept that '*similia similibus solventur*' becomes a stringent requirement; in terms of Hildebrand's solubility concept, this means that a polymer can dissolve only in fluids whose solubility parameters are very closely related